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FAKULTÄT FÜR PHYSIK UND ASTRONOMIE

50 Jahre

PSTP 2015

RUB

Polarized Sources, Targets and Polarimetry

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BROOKHAVEN NATIONAL LABORATORY

New DAQ for the HJET polarimeter at RHIC

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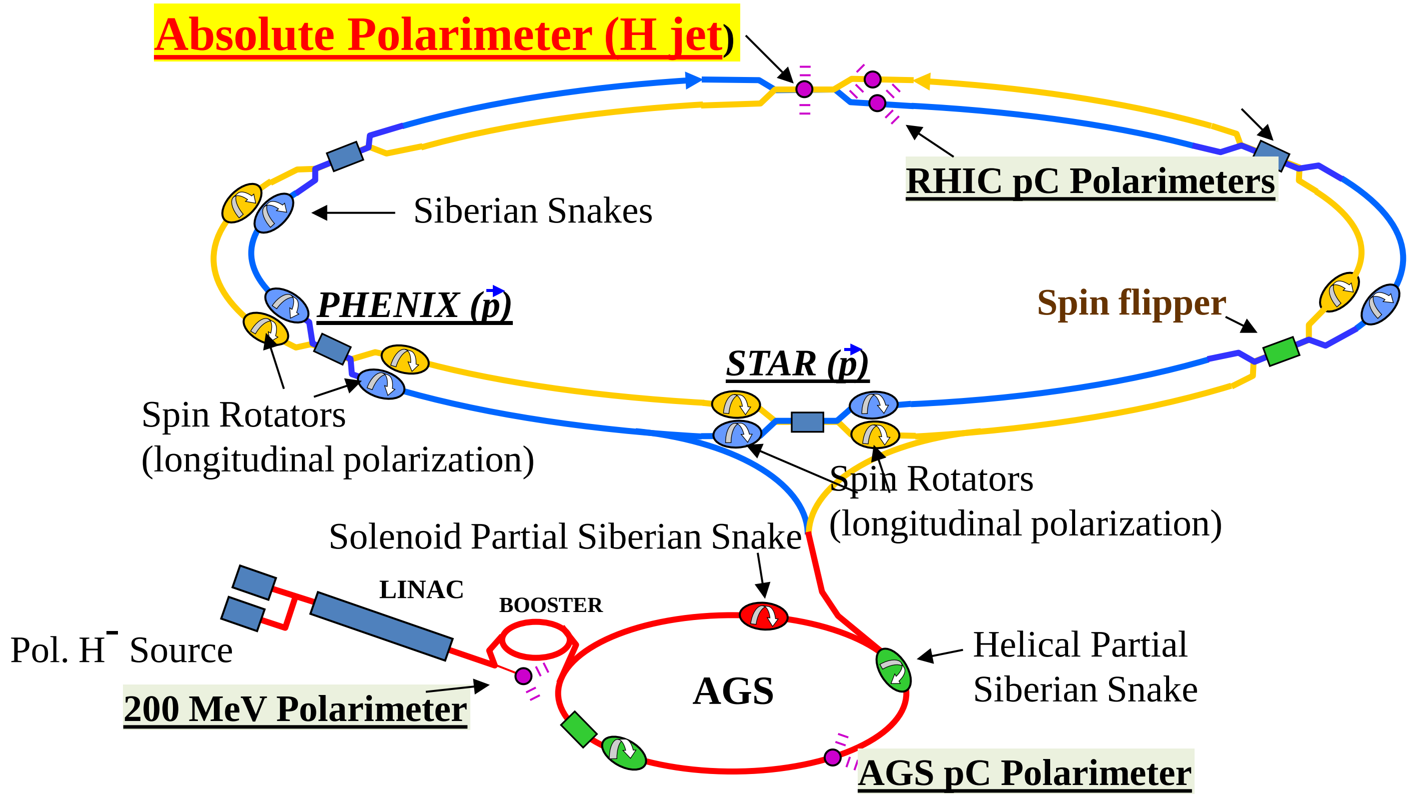
Polarized Proton Beams at RHIC



H-Jet polarimeter: (96 channels)

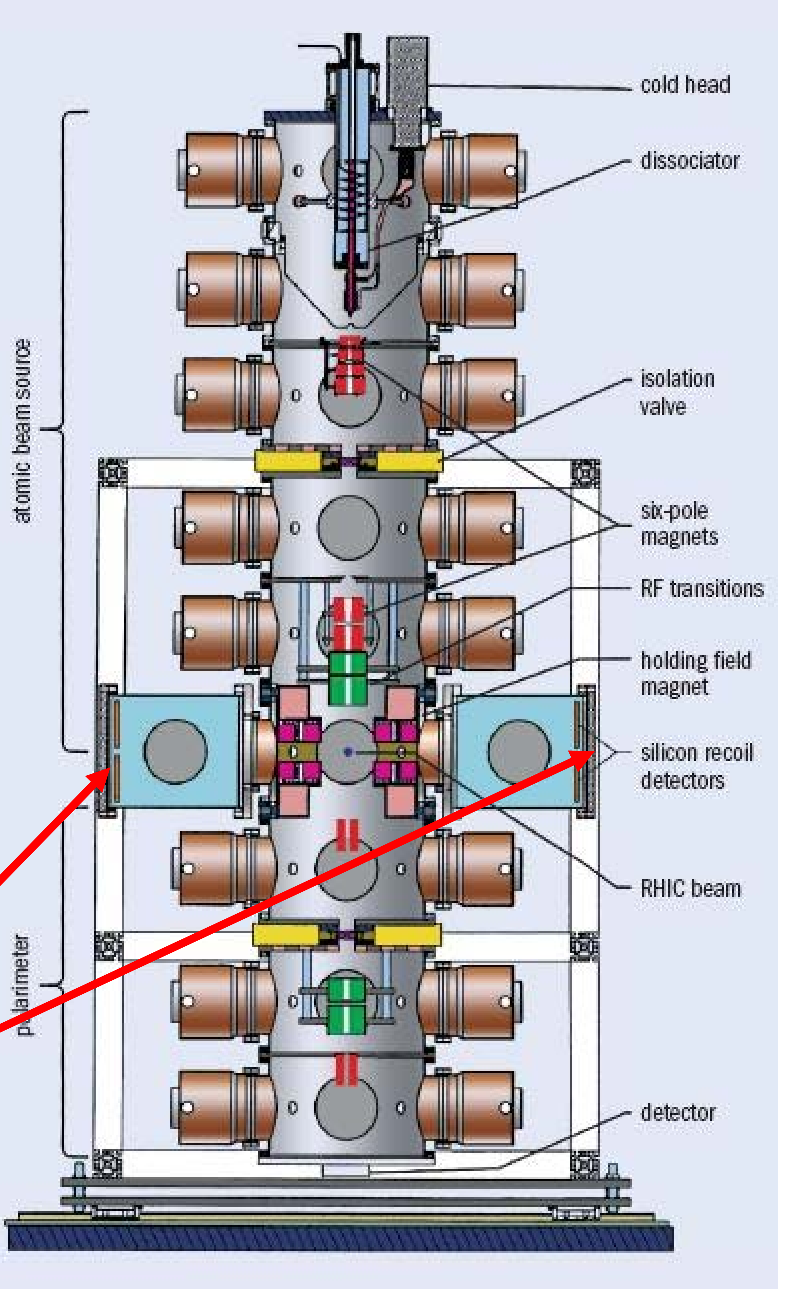
- measure average (absolute) polarization of RHIC beams

Polarized Atomic Hydrogen Gas Jet Target (HJET)

- The HJET polarimeter was commissioned in 2004.
- It was designed to measure absolute polarization of 24-250 GeV/c proton beams with systematic errors better
- $\Delta P/P \leq 0.05$
- The atomic hydrogen polarization in the Jet is about 96%
- The Jet polarization is flipped every 5 min.

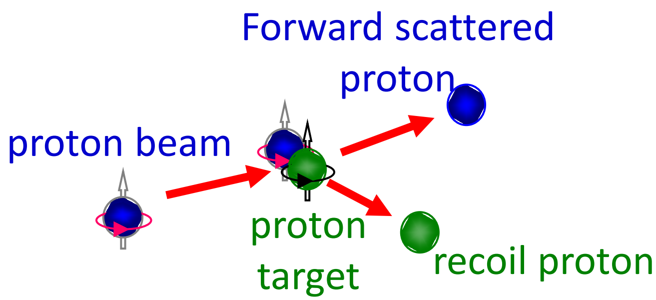
New in Run 2015:

- 500 μm Hamamatsu detectors
- DAQ based on VME 250 MHz 12 bit FADC250 (JLab) wave form digitizers.



Recoil detectors
ToF, T_{REC}, θ_{REC}

Beam Polarization Measurement in HJET



$$t = (p_{out} - p_{in})^2 = -2m_p T_R$$

$$\frac{z - z_{jet}}{L} \approx \theta_R \approx \sqrt{\frac{T_R}{2m_p}\frac{E_{beam} + m_p}{E_{beam} - m_p}}$$

In elastic pp scattering, the asymmetry of low energy ($T_R < 10\ MeV$, $90°$) recoil protons is measured.

$$a = \frac{N_L - N_R}{N_L + N_R} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = A_N(t)\ P$$

For left/right symmetric detectors and spin flipping measurements, the systematic errors may be strongly suppressed

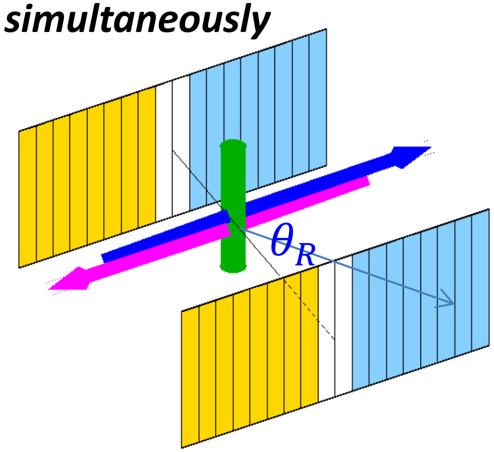
$$a = \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_R^{\uparrow} N_L^{\downarrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_R^{\uparrow} N_L^{\downarrow}}}$$

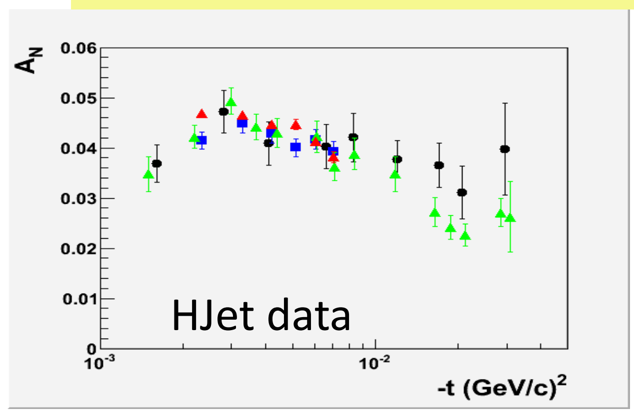
Both, beam and jet asymmetries are measured simultaneously

$$a_{beam} = A_N(t)\ P_{beam} \qquad a_{jet} = A_N(t)\ P_{jet}$$

$$P_{beam} = \frac{a_{beam}}{a_{jet}} P_{jet}$$

Both RHIC beams (Blue and Yellow) are measured simultaneously





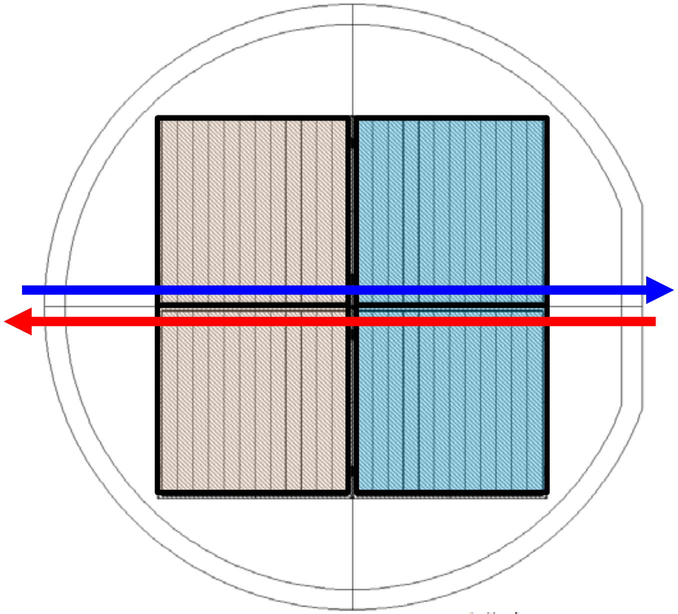
Analyzing power:

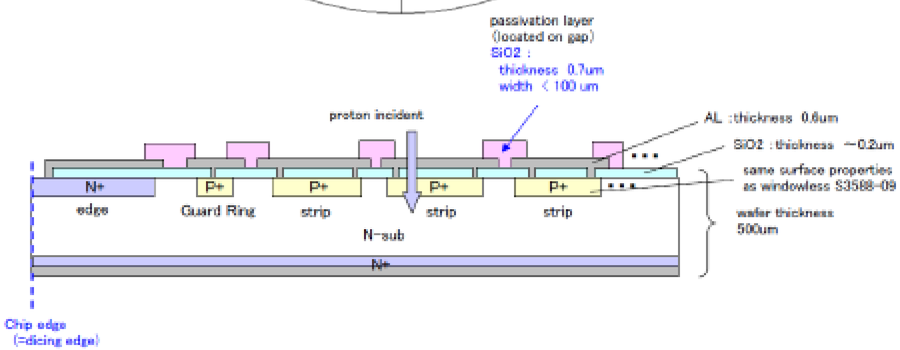
$$A_N(t) \sim 0.04$$

24 GeV: PRD 79, 094014(2009)
31 GeV: Preliminary
100 GeV: PLB 638 (2006) 450
250 GeV: Preliminary

New Silicon Detectors
(Hamamatsu Photonics K.K. S10938-3627)

Four detectors on one side:





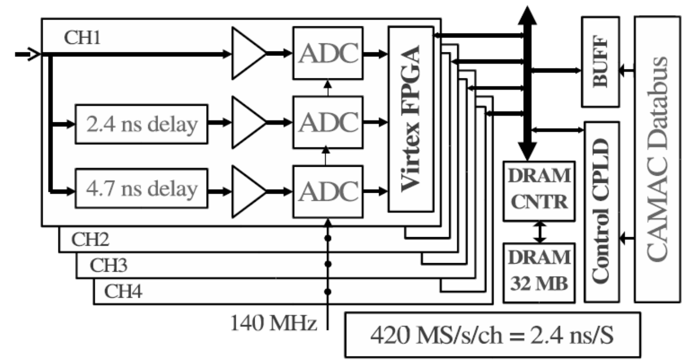
8 detectors (12 strips per detector)	
Detector size	$45 \times 45\ mm^2$
Gap between detectors	$\approx 19\ mm$
Strip size	$3.7\ \times 45\ mm^2$
Gap between strips	$50\ \mu m$
Depletion region	$470\ \mu m$
Uniform Dead-layer	$\sim\ 0.37\ mg/cm^2$
Distance to the beam	$770\ mm$
Bias Voltage	$150\ V$

- ***The detector geometry allows to detect recoil protons (elastic pp) with kinetic energy up to $11\ MeV$.***
- ***Protons with energy above $7.8\ MeV$ punch through the detector (only part of kinetic energy is detected).***
- ***An ability to proper reconstruction of the punch through protons was an important requirement for the new DAQ.***

Old CAMAC based DAQ (2004-2015)

- 2 CAMAC Crates (USB connection to PC)
- 24 WFD Boards (Yale University)
  - *4 channels per board*
  - *8 bit*
  - *140 MHz (effectively 420 MHz)*
  - *Custom Firmware (deadtime-less)*
  - *External signals:*
    - *Clocks derived from 28.15 MHz RF signal*
    - *Bunch Zero (every beam rotation)*
    - *Veto*
    - *Delimeter*
- External signal (Jet polarization status)
- CAMAC I/O registers and NIM electronics

Simplified block diagram of one WFD channel

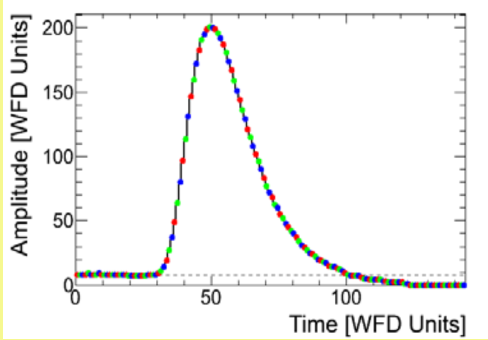


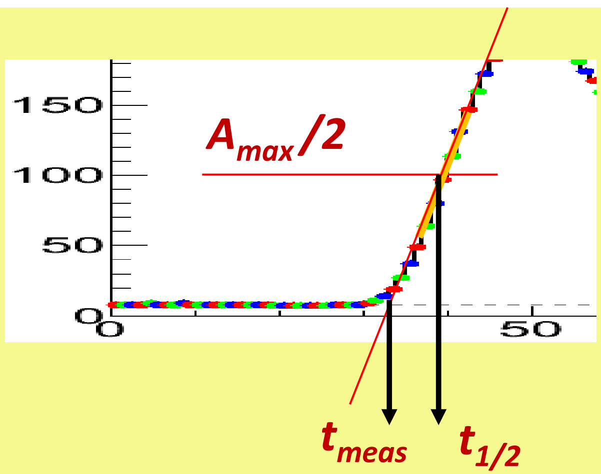
The DAQ was used in the first part of the RHIC Run15.

Signal Amplitude and Time:

(Δt may be used as a parameterization for waveform shape)

$$\Delta t = \frac{A_{max}/2}{dA/dt} = t_{1/2} - t_{\rm meas}$$





New VME based DAQ (2015-…)

- Wiener VME 64x crate + Single Board Computer
- 6 FADC Boards (Jefferson Lab)
  - *16 channels per board*
  - *12 bit*
  - *250 MHz*
  - *General Purp. Firmware*
    - *internal trigger*
    - *deadtime-less*
    - *raw waveform available*
  - *External signals:*
    - *244 MHz Clocks derived from 28.15 MHz RF signal*
    - *Sync Reset (every Jet Cycle, ~5 min)*
- Front Panel Signal Distribution Module (Jefferson Lab)
- BNL V128 Input-register (Jet polarization status)

Total Rate in HJET ~ 10 kHz (2 Mbyte/s) allows us to use FADC general purpose firmware and acquire raw waveforms (80 samples -> 328 ns)

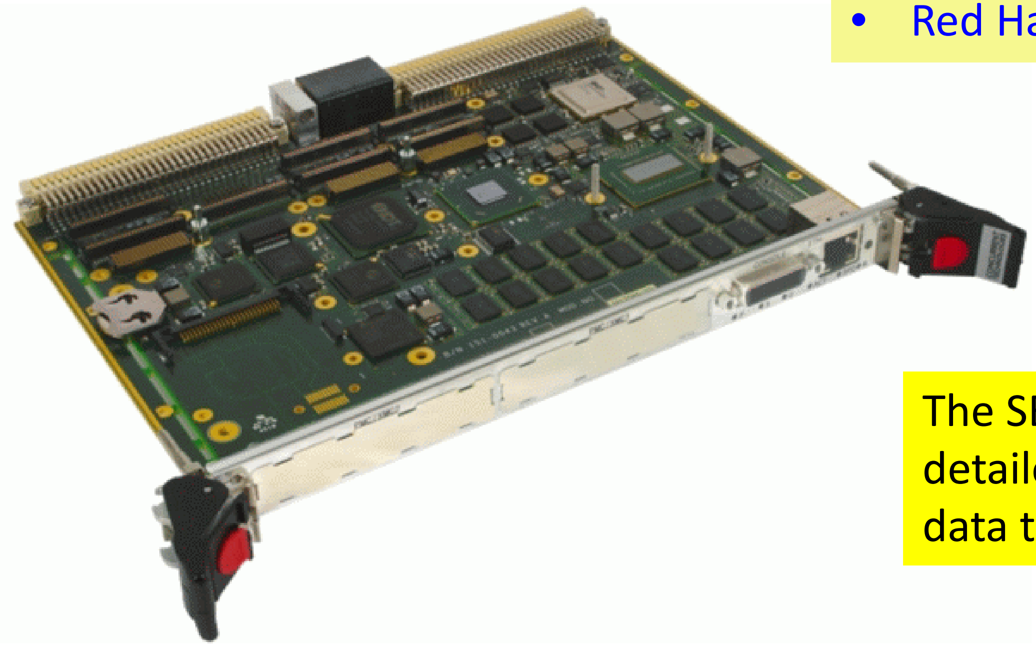
- *The new DAQ was assembled without destroying the old DAQ. The infrastructure of the old DAQ was employed in the new one.*
- *It takes only about 30 min. to switch between DAQ's (reconnection of 96 signal cables)*
- *A software interface to use new data format with old analysis was developed.*
- *This allows us to migrate to new DAQ smoothly.*
- *New data analysis was also developed.*

Single Board Computer (SBC)

CONCURRENT TECHNOLOGIES

VX 915/011-14

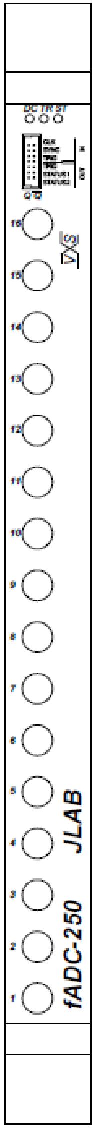
- 4-core 2.1 GHz Intel Core i7-3612QE Processor
- 16 Gbytes DDR3-1600 DRAM with ECC
- VME64 interface supporting A64/A32/A24/A16/D64/D32/D16/D8(E0), MBLT64, 2eSST and 2eVME
- 500 Gbyte Hard Drive
- Red Hat Enterprise 6 Linux



The SBC is powerful enough to provide detailed online analysis in parallel with data taking.

FADC250

The board was designed for the Jlab Hall D.



fADC250

VME64x Flash ADC Module Specifications

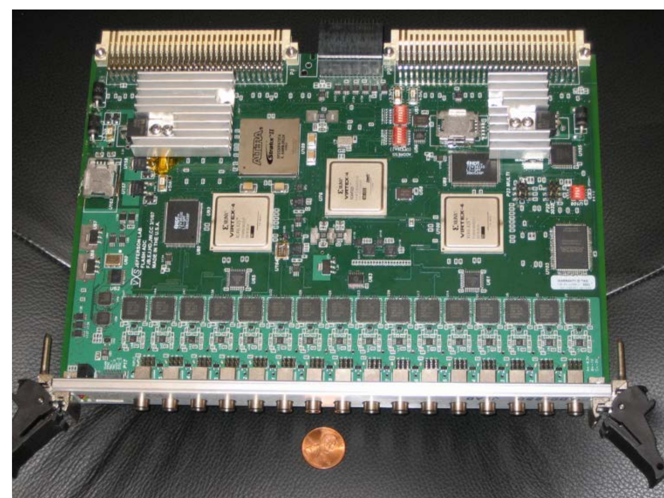
Signal Inputs	Number	16 S Version (50 Ohm, LEMO)*
	Range	-0.5V, -1V & -2V. User Selectable
	Offset	±10% FS per channel via DACs
Clock	Sampling	250 MSPS, Differential
	Jitter	1 pS (10-bit ADC), 350 fS (12-bit ADC)
	Source	Internal and External
Control Inputs/Outputs	Clock	IN – Diff., LVPECL (Front Panel & Backplane)
	Trigger	IN, OUT - Differential (Front Panel - Backplane)
	Status 1	OUT – Differential (Front Panel & Backplane)
	Status 2	OUT – Differential (Front Panel & Backplane)
	Sync	OUT – Differential (Front Panel & Backplane)
	Trigger SW	Software Strobe (Internal)
Conversion Characteristics	Resolution	10-bit (8 and 12-bit by chip replacement)
	INL	± 0.8 LSB
	DNL	± 0.5 LSB
	SNR	56.8 dB @ 100 MHz Input
	Data Latency	32 nS
Trigger Latency	8 µS	
Data Memory	8 µS	
Data Processing	Sparcification	
	Windowing	
	Charge, Pedestal, Peak	
	Time (Over Threshold, Relative to trigger)	
	Output (Backplane, VXS)	
Interface	VME64x – 2eVME Data Transfer Cycles (40, 80, 160 & 320 MB/sec) with VXS-P0	
Packaging	6U VME64x	
Power	+3.3V, +5V, +12V, -12V	

- ***16 Channel***
- ***12 bit, 250 MHz***
- *Internal Trigger , deadtime free*
- ***Waveform length up to 511 samples (2 µs)***
- ***Dead Time Free***

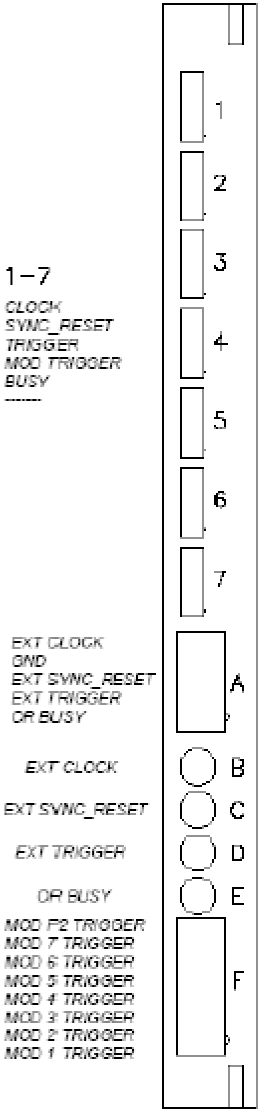
External Inputs:

(from the Signal Distribution Card)

- ***Trigger***
- ***Sync Reset***
- ***Clocks***



Front Panel Signal Distribution Module for the FADC250 (FP-SD)



The board was designed for the Jlab Hall D.

- *The SD-FP distributes synchronized Clock, Trigger, and Sync Reset signals to up to 7 FADC250 boards.*
- *Supports external and internally generated signals*

For RHIC Run15 we borrowed 7 FADC 250 boards and FP-SD from JLab.

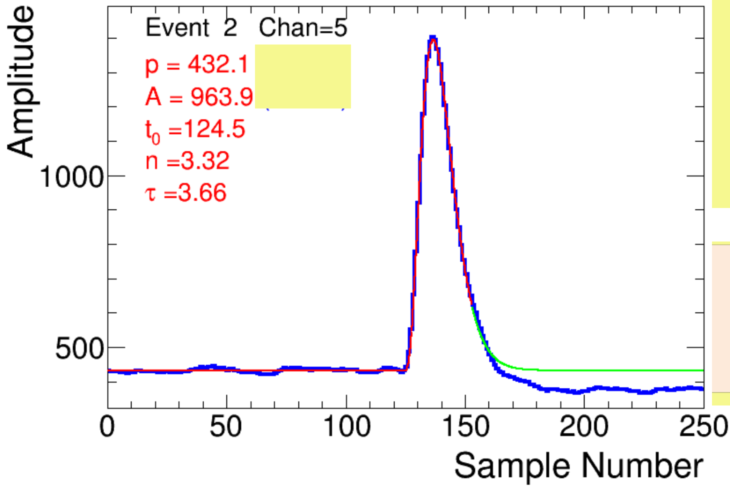
We have got significant help from Jlab Fast Electronics Group.
FADC Firmware was upgraded in accordance with our requirements.

We acknowledge the outstanding contribution of
Chris Cuevas, Hai Dong, Ed Jastrzembski, and Bryan Moffit
to the development the new DAQ for the Hjet polarimeter at RHIC.

Waveform Processing

Two processing methods were implemented

1. ***The same as for CAMAC DAQ (finding maximum amplitude and rising edge slope)***
2. ***Waveform Fit***



Signal parametrization:

$$W(t) = p + A\,(t - t_i)^n \exp\left(-\frac{t-t_i}{\tau_s}\right)$$

$$t_m = t_i + n\tau_s$$

- measured waveform (blue)
- fit function $W(t)$ (red)
- continuation of the fit function (green)

t_i is proton input time to the detector.
t_m is time of the signal maximum.
t_m is more stable in the fit.

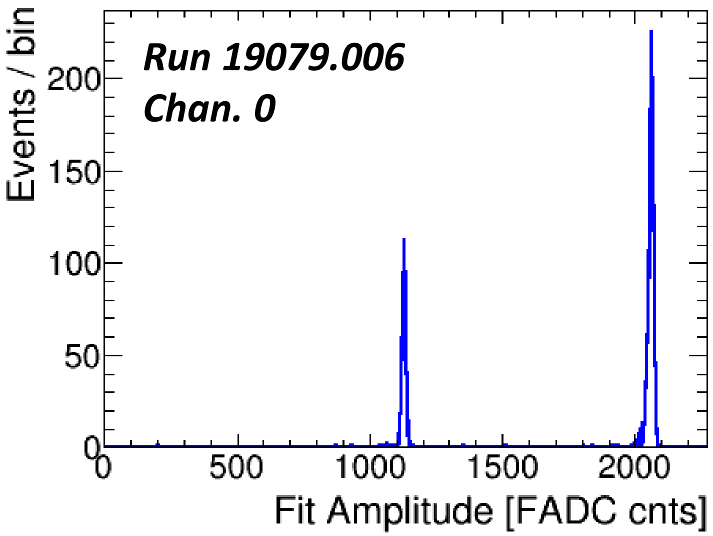
To isolate recoil proton the time of flight energy is compared with energy deposited in detector:

Waveform $\rightarrow$ Signal amplitude (***A***) and time (***t***)

$$E_{\text{kin}} = \frac{M_p L^2}{2(t - t_0)^2} = \alpha A + E_{\text{loss}}(A, x_{\text{DL}})$$

Parameters α, t_0, and x_{DL} are determined in the calibration

Calibration Using Alpha-sources



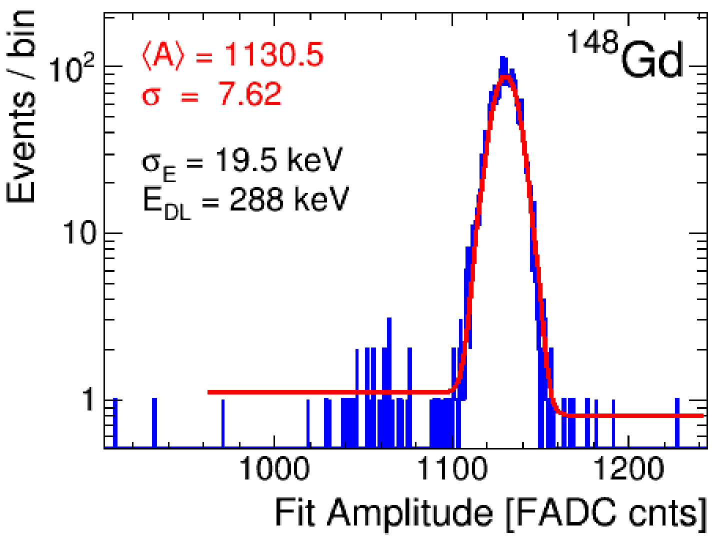
All Si detectors are exposed by 2 α-sources:

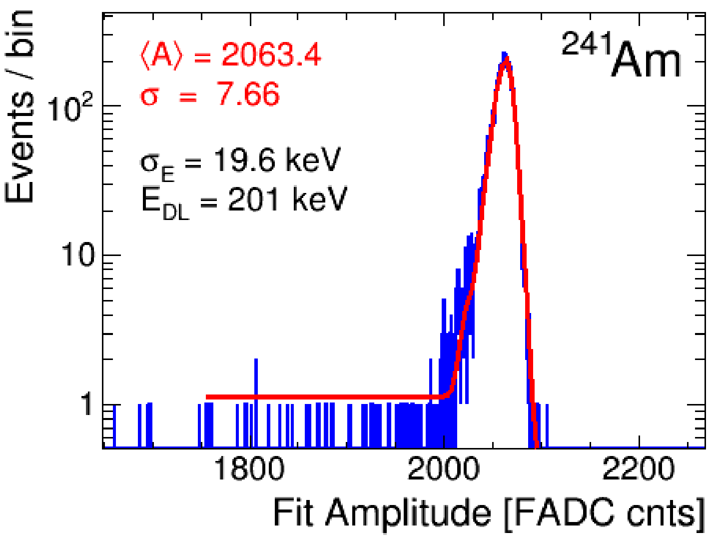
$^{148}Gd\ \ (3.183\ MeV)$

$^{241}Am\ \ (5.486\ MeV)$

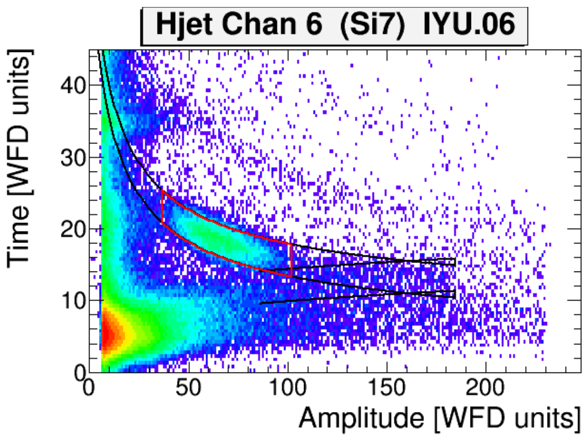
Gain ($\alpha \sim 2.5\ \ keV/cnt$) and dead-layer thickness ($x_{DL} \sim 0.37\ mg/cm^2$) were measured for every Si strip.

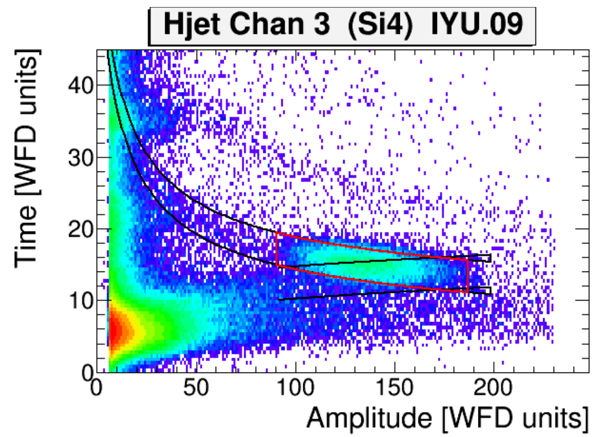
Energy resolution $\sigma_E\ \approx\ 20\ keV$ is dominated by electronic noise.
(For CAMAC DAQ $\sigma_E \sim 30\ keV$)

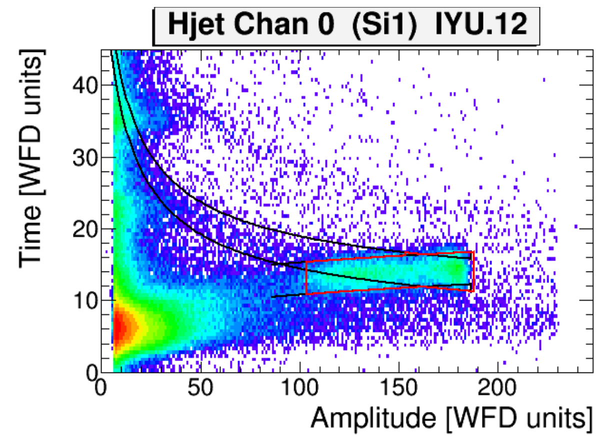




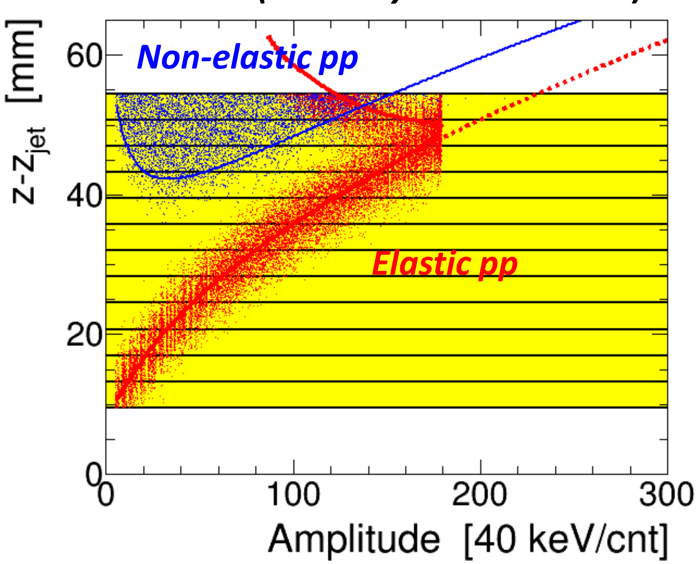
Good Event Isolation







Simulation (arbitrary normalization)



Elastic pp: $p + p \to p + p$

$$z \approx L\sqrt{\frac{T}{2m_p}}$$

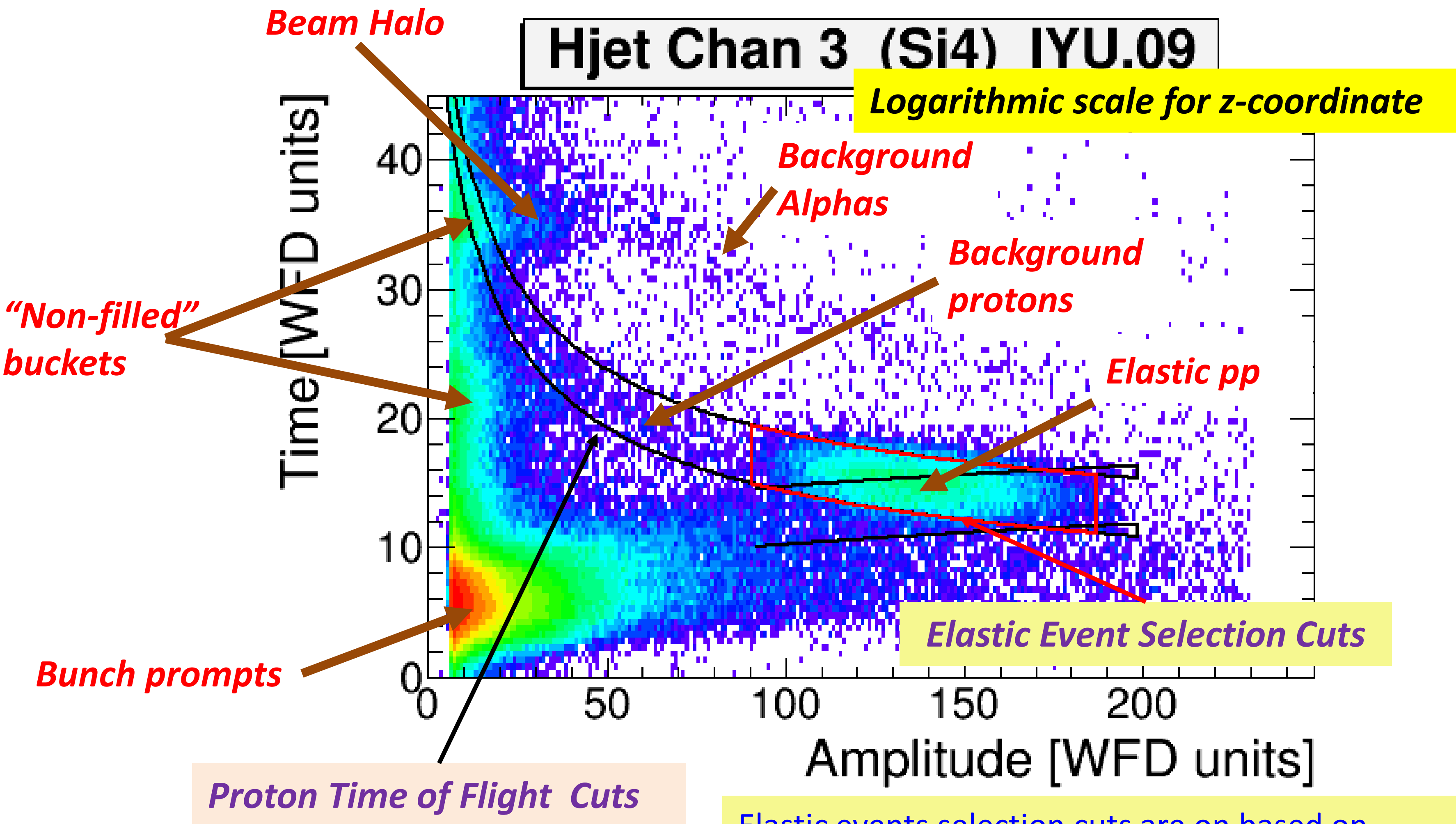
Non-elastic pp: $p + p \to p + p + \pi$

$$z \geq L\sqrt{\frac{T}{2m_p}}\left(1 + \frac{m_p m_\pi}{E_{beam} T}\right)$$

Background: $p + A \to p(\alpha, \dots) + X$

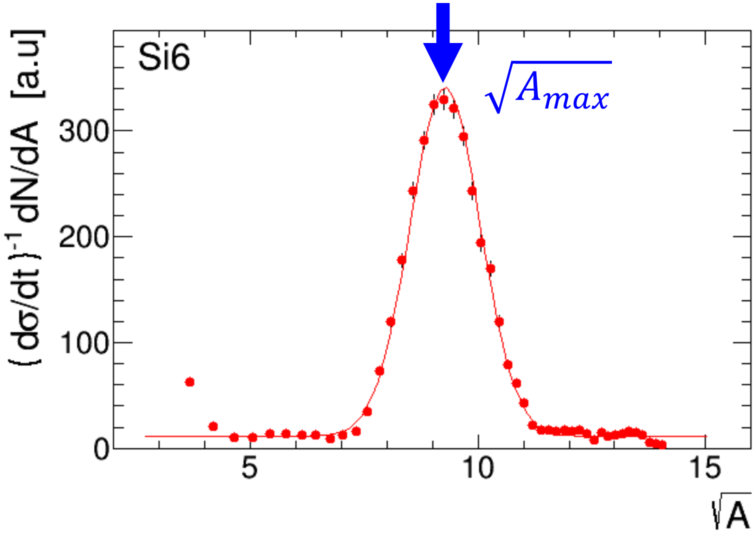
same signals in all strips

Beam Halo: $\sim 1.5\ MeV$ *signals produced by beam halo MIP's. Correlated with beam buckets. Same signals in allstripss*



Elastic events selection cuts are on based on $t - t_p(E)$ and $\sqrt{E} - \sqrt{T_{\text{strip}}}$ cuts,
where t and E are measured time and energy,
$t_p(E)$ is proton time corresponding energy E,
and T_{strip} is proton kinetic energy corresponding considered Si strip.

Geometry Based Calibration

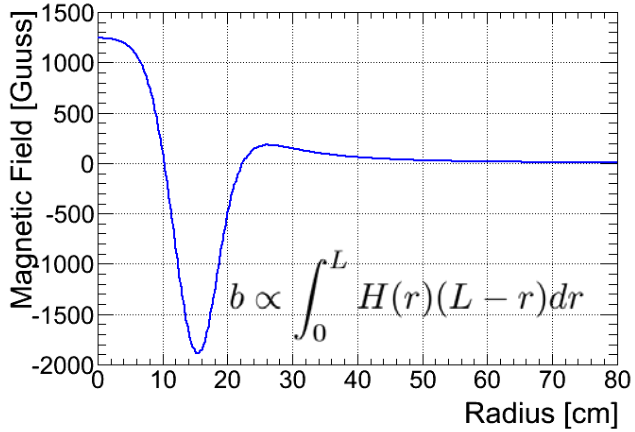


For elastic pp only scattering, the recoil proton distribution on $\sqrt{A}$ may be considered as an image of jet / beam gas z-coordinate profile (smeared by strip width), because $\sqrt{A} \propto \sqrt{T} \propto (z_{\text{strip}} - z_{jet})$

$$\sqrt{A_{max}} \Leftrightarrow \sqrt{T_{\text{strip}}} = \sqrt{2m_p \frac{E_{\text{beam}} - m_p}{E_{\text{beam}} + m_p} \frac{z_{\text{strip}}}{L}}$$

This is a calibration equivalent to the calibration with α- source.

Holding Field Correction:

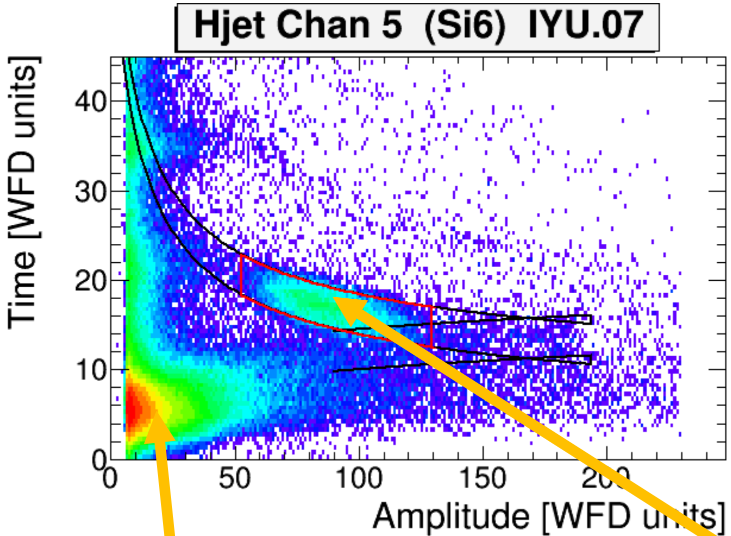


$$\frac{z}{L} = \sqrt{\frac{T}{2M_p} \frac{E_{\text{beam}} + M_p}{E_{\text{beam}} - M_p}} \pm \frac{b}{L\sqrt{2M_pT}}$$

In real world, $T_{\text{strip}} = T_{\text{strip}}(z_{\text{strip}}, p_i)$,
Where p_i are corrections including z-coordinate misalignments of eight Si detectors, magnetic field corrections for left and right side. In turn, corrections p_i depend on beam angle and x-coordinate.

Corrections p_i have to be determined before geometry based calibration can be used.

Control for the Beam / Detector Geometry



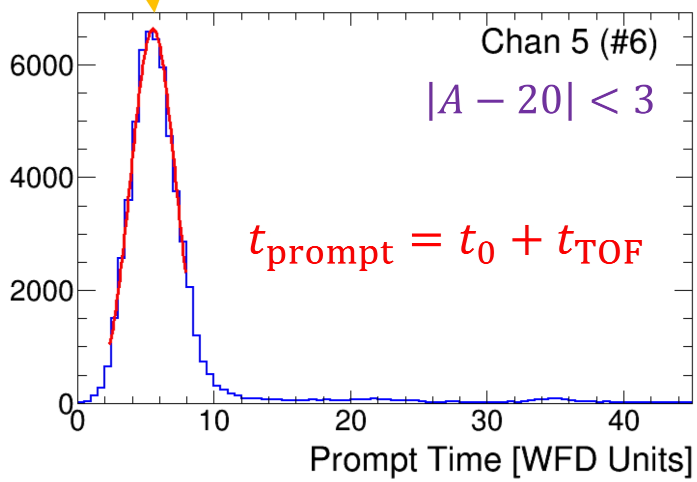
For every acceptable strip we can compare elastic peak time t_{max} and prompt time t_{prompt}. The prompt time of flight time t_{TOF} is assumed to be the same for all strips.

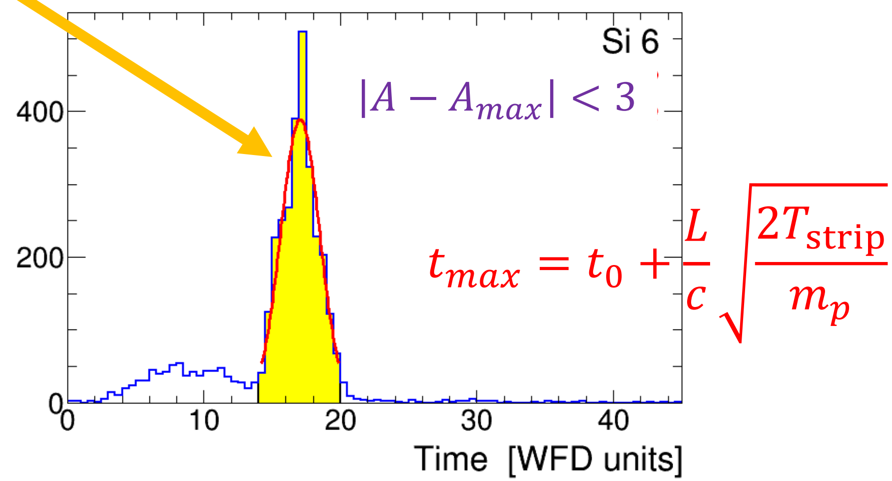
Correction parameters and prompt time of flight may be found by minimizing

$$\chi^2 = \sum_{\text{strips}} \left(t_{\text{prompt}} - t_0(p_i) - t_{\text{TOF}}\right)^2$$

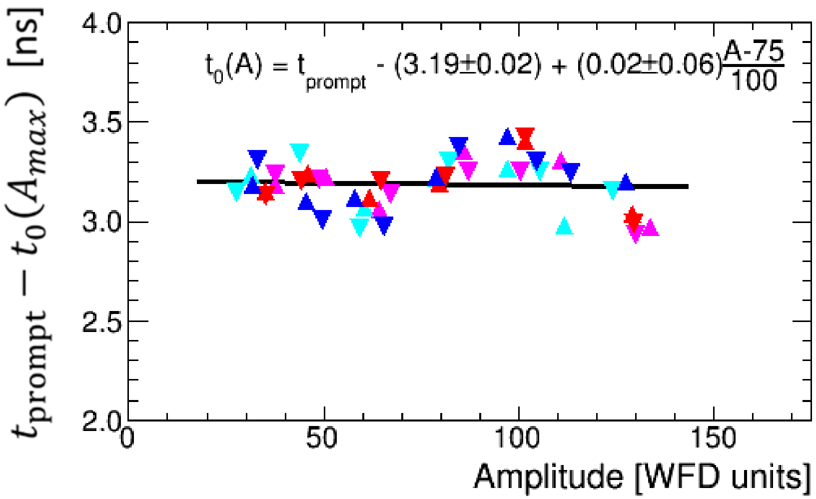
where

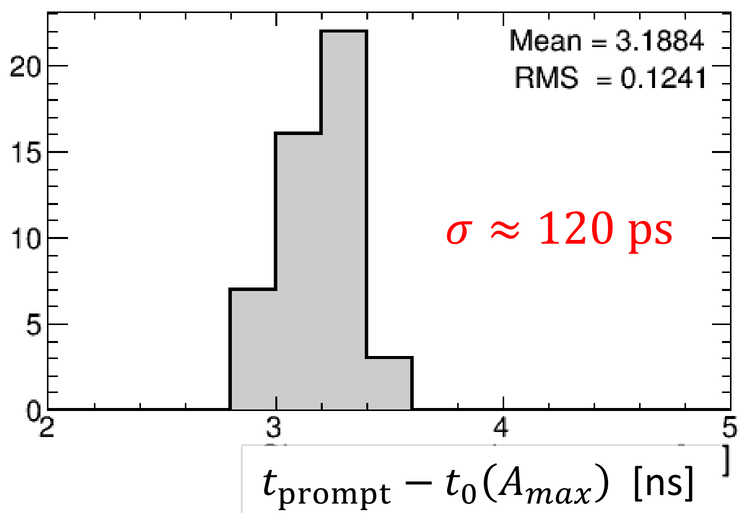
$$t_0(A_{max}, p_i) = t_{max} - \frac{L}{c}\sqrt{\frac{2T_{\text{strip}}(p_i)}{m_p}}$$





Time Alignment

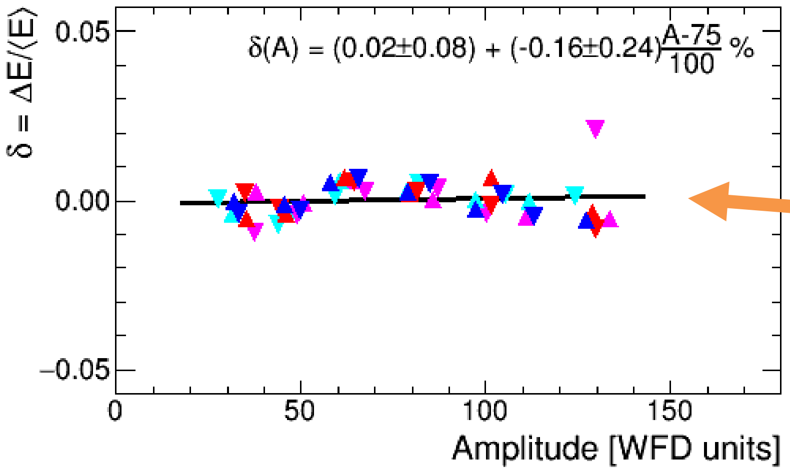




For CAMAC DAQ $\sigma \sim 300$ ps

- For each Si strip time offset t_0 can be determined with accuracy better 120 *ps* from prompt time measurements.
- Some systematic dependence of measured time on amplitude is observed. Proper accounting of these dependence will improve accuracy of time alignment.
- The positions of all detectors may be reconstructed with accuracy $\sim 100\ \mu m$.
- Variations of magnetic field and beam direction and x-coordinate may be monitored with accuracy equivalent to $\sim 100\ \mu m$.

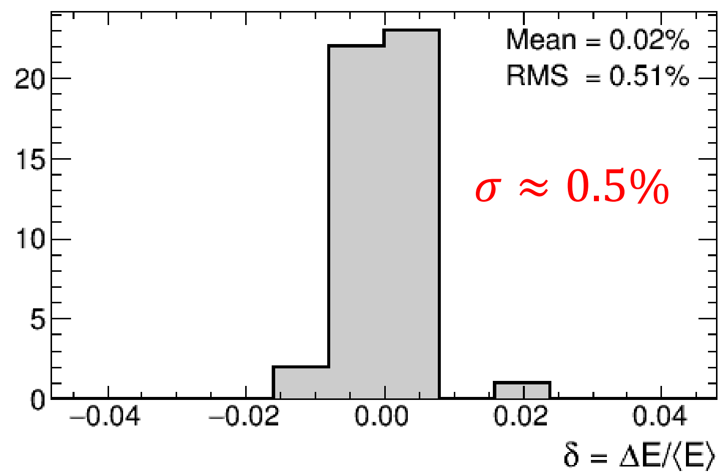
Comparison of geometry based and alpha-calibrations.



The geometry based and alpha calibrations are absolutely independent, but they may be directly compared.

$$\Delta E = T_{\mathrm{strip}} - E_{cal}(A_{max}, \alpha, x_{\mathrm{DL}})$$

For proton energy range 1-6 MeV the calibrations were found to be consistent within 0.5% precision



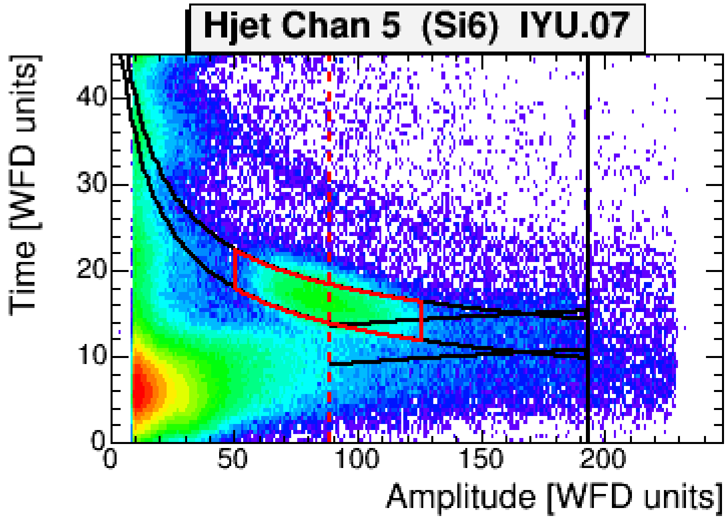
For CAMAC DAQ $\sigma \sim 1.5$ %

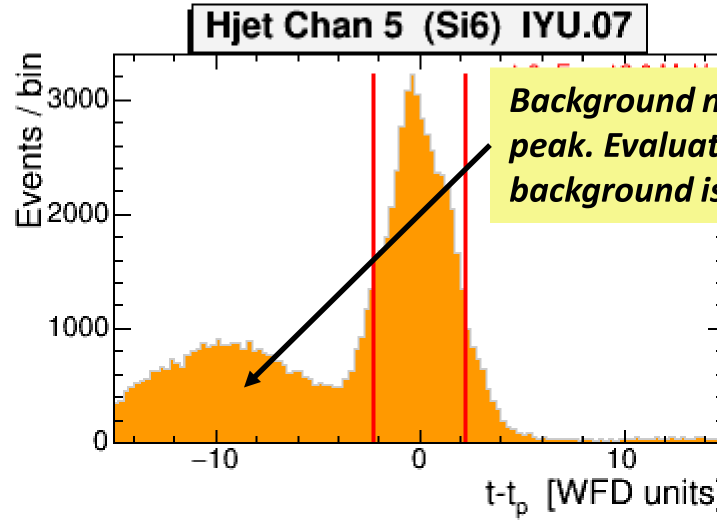
Systematic errors in energy calibration

$(\sigma_E/E)_{syst} < 0.5\%$ $(< 025\%\,?)$

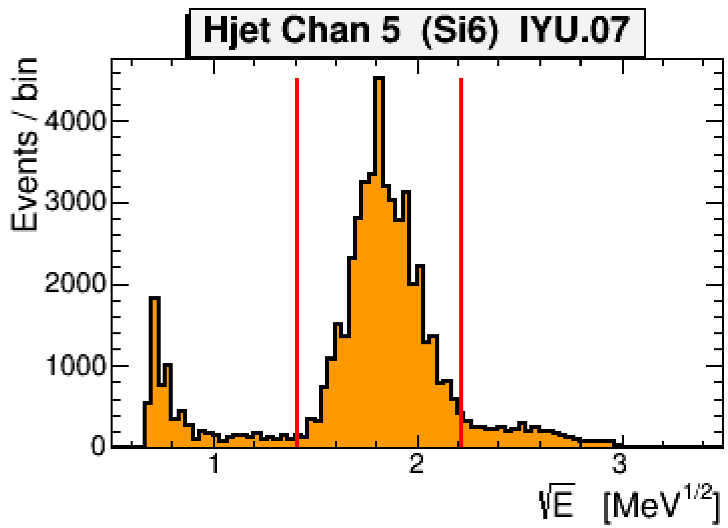
8-hour run followed immediately after alpha-calibration run was used for geometry based calibration. In 24 hours the consistency of two calibrations were degraded to 0.7%.

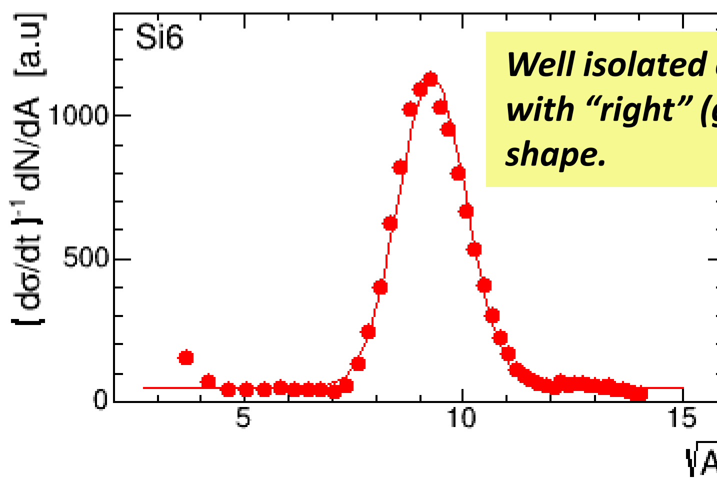
Event distributions for stopped protons





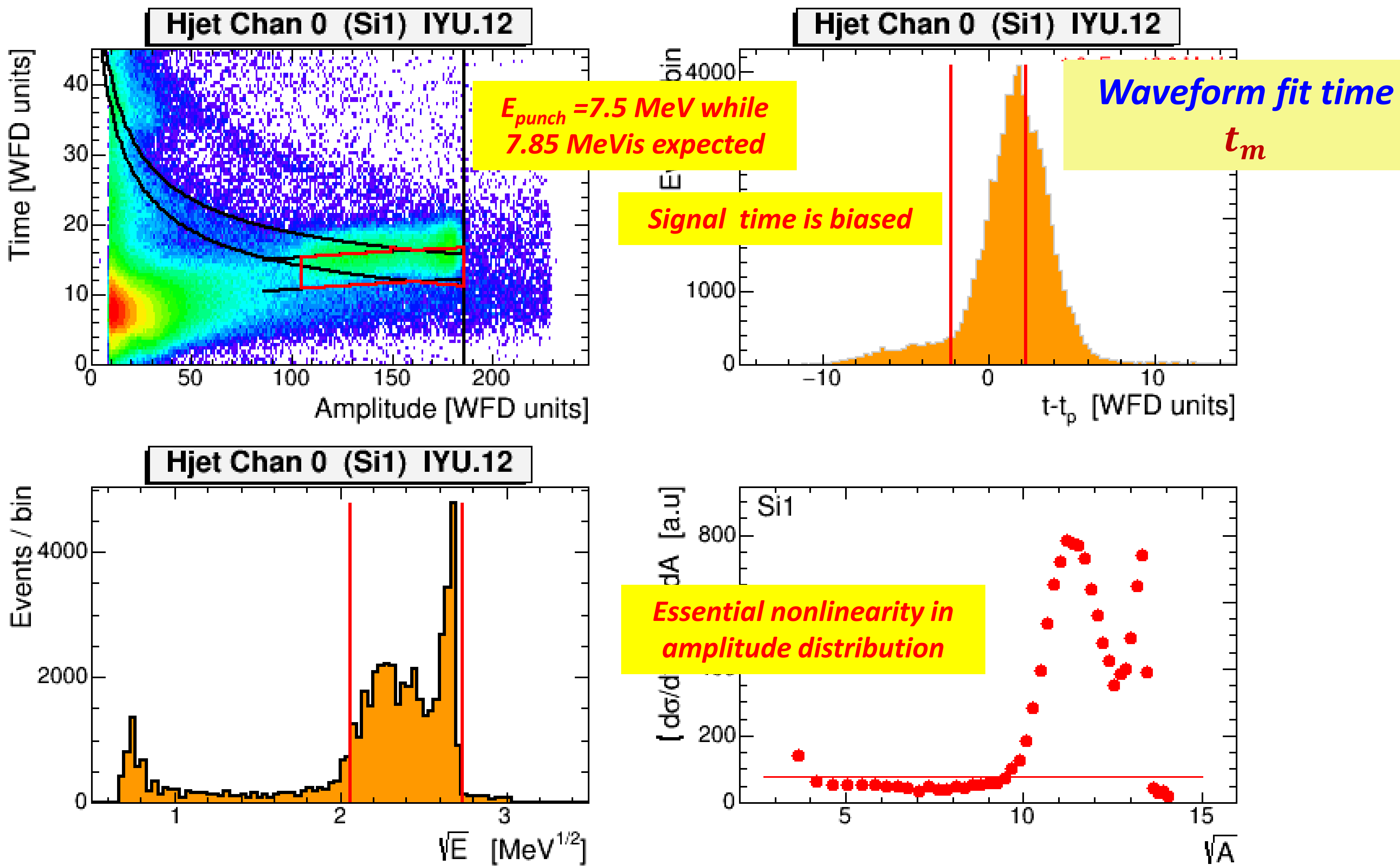
Background near the signal peak. Evaluation under background is needed.





Well isolated elastic signal with "right" (gaussian) shape.

Event distributions for punched through protons



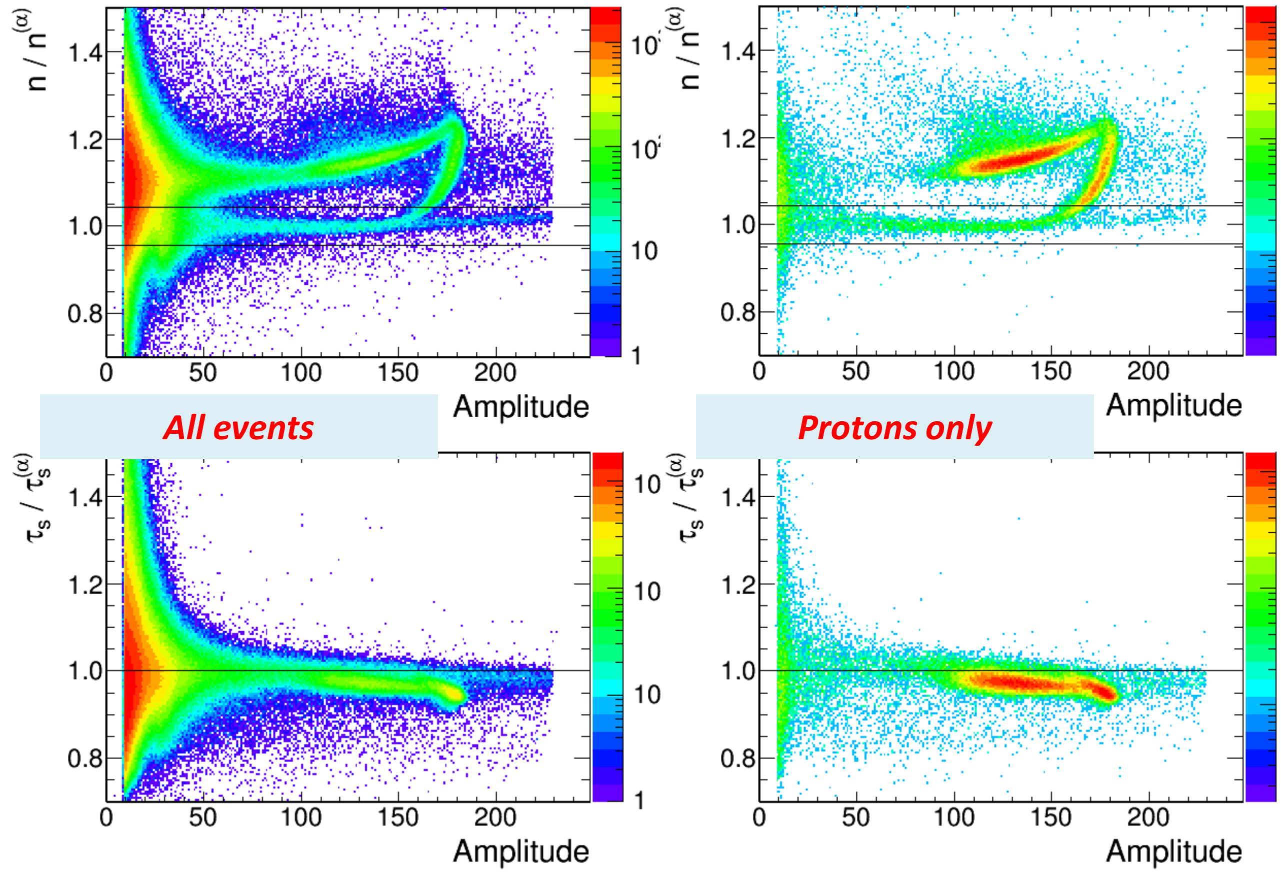
Above 5 MeV stopped and punched through proton signals are strongly overlapped in time – amplitude distributions.

Dependence of waveform fit parameters on amplitude

The distributions are for Si1 (the strip with elastic punched through protons)

$n^{(\alpha)}$ and $\tau^{(\alpha)}$ are waveform fit parameters determined in alpha calibration.

The waveform shape is stable for proton energies up to 6 MeV. Than, it changes significantly.



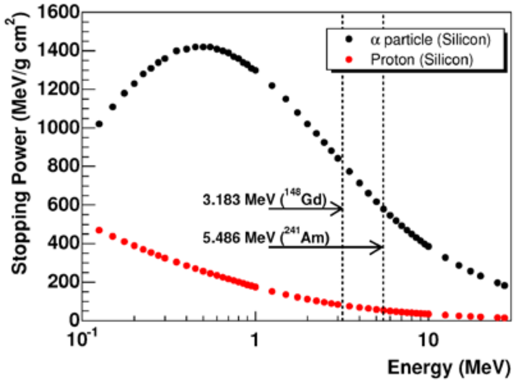
Fluctuations of n and τ_s in the fit are strongly correlated:

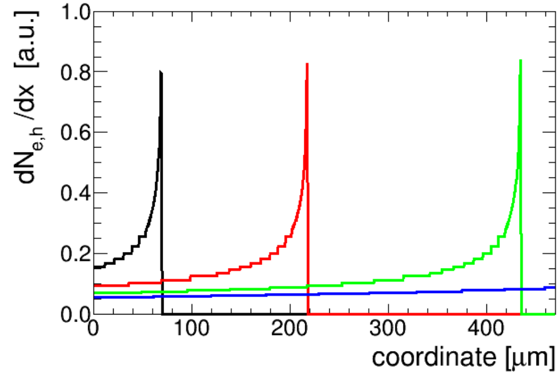
1. **We should account the correlation**
2. **We can fix τ to $\tau^{(\alpha)}$**

We need not only describe the dependence $n = n(A)$, but also properly parameterize it:
$n = n(E_{kin})$ and $A = A(E_{kin})$

Signal Simulation

Ionization losses:

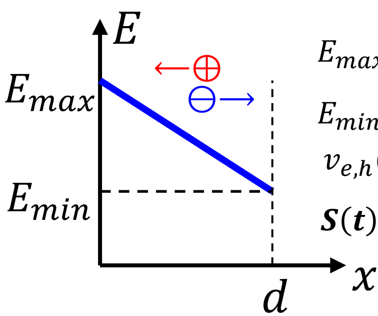




Proton Energy

- 2.5 MeV
- 5.0 MeV
- 7.5 MeV
- 10.0 MeV

Charge Collection:

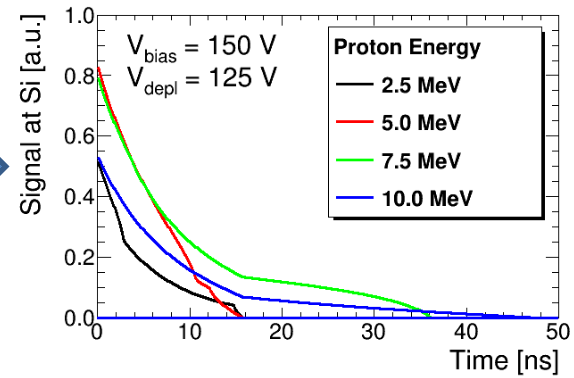


$$E_{max} = \frac{V_{bias} + V_{depl}}{d}$$

$$E_{min} = \frac{V_{bias} - V_{depl}}{d}$$

$$v_{e,h}(x) = \mu_{e,h} E(x)$$

$$\boldsymbol{S(t) \sim |v_e(t)| + |v_h(t)|}$$



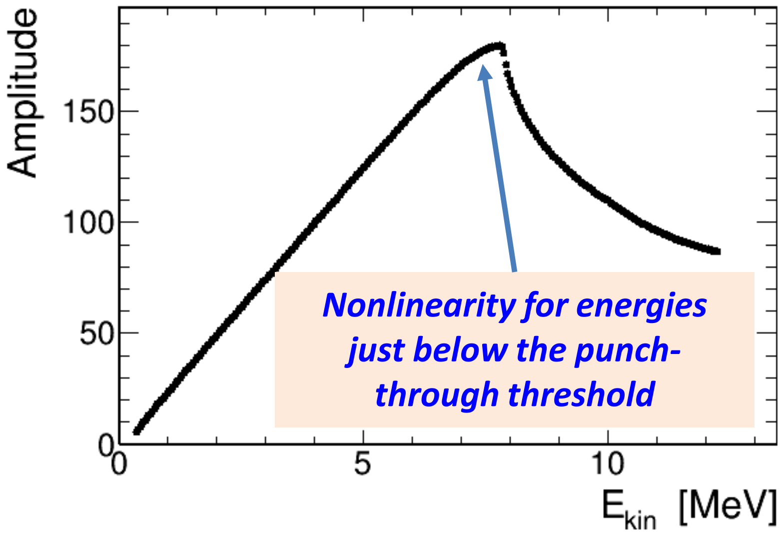
The depletion voltage $V_{depl} = 125$ V was selected for the best fit of the data

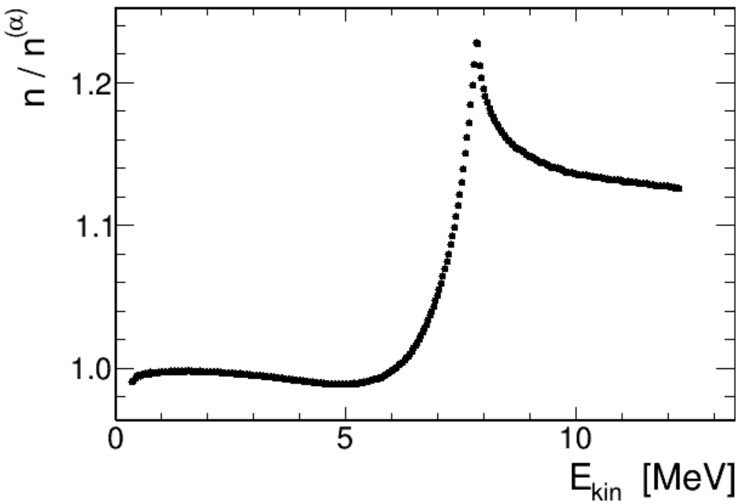
Digitization:

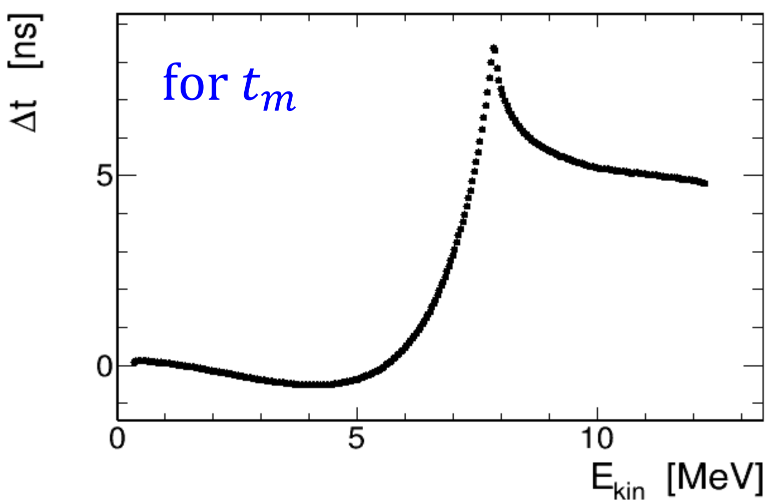
$$A(t) \propto \int S(\tilde{t})(t - \tilde{t})^n e^{-(t-\tilde{t})/\tau}\, d\tilde{t} \;\Rightarrow\; A_i$$

^{241}Am signal was simulated to parameterize digitization

Predictions for waveform parameters dependence on proton kinetic Energy



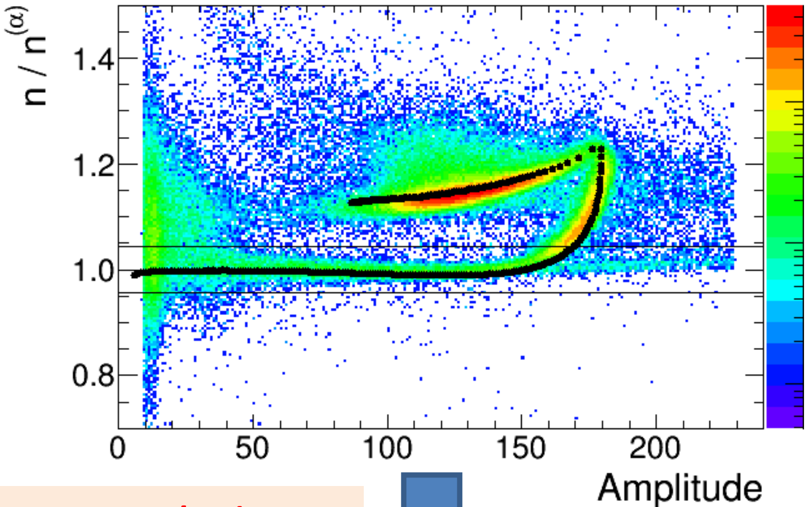




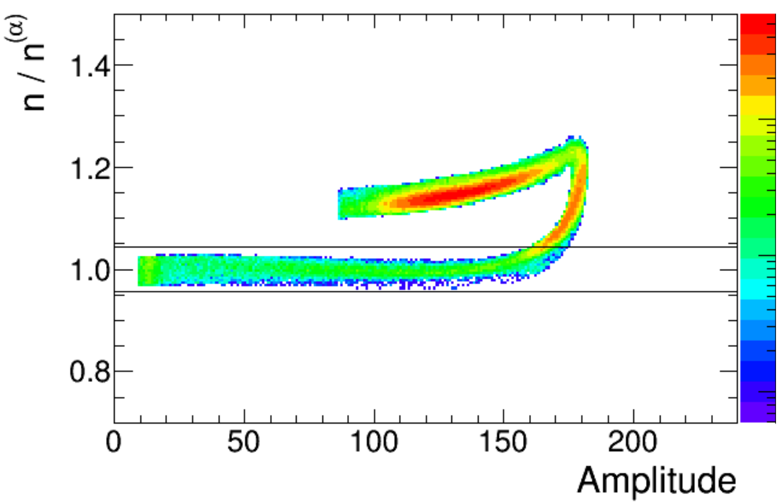
Δt is variation of measured time caused by waveform shape dependence on kinetic energy (actually, the systematic error in measurements). The offset was arbitrarily chosen as

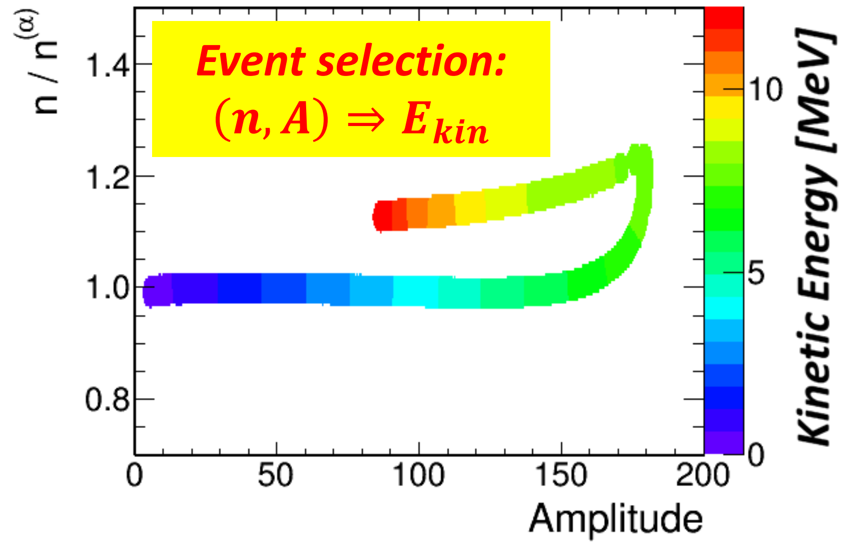
$$\Delta t(E_{kin} = 5.486\ MeV) = 0$$

Simulation vs Experimental Data



Event selection

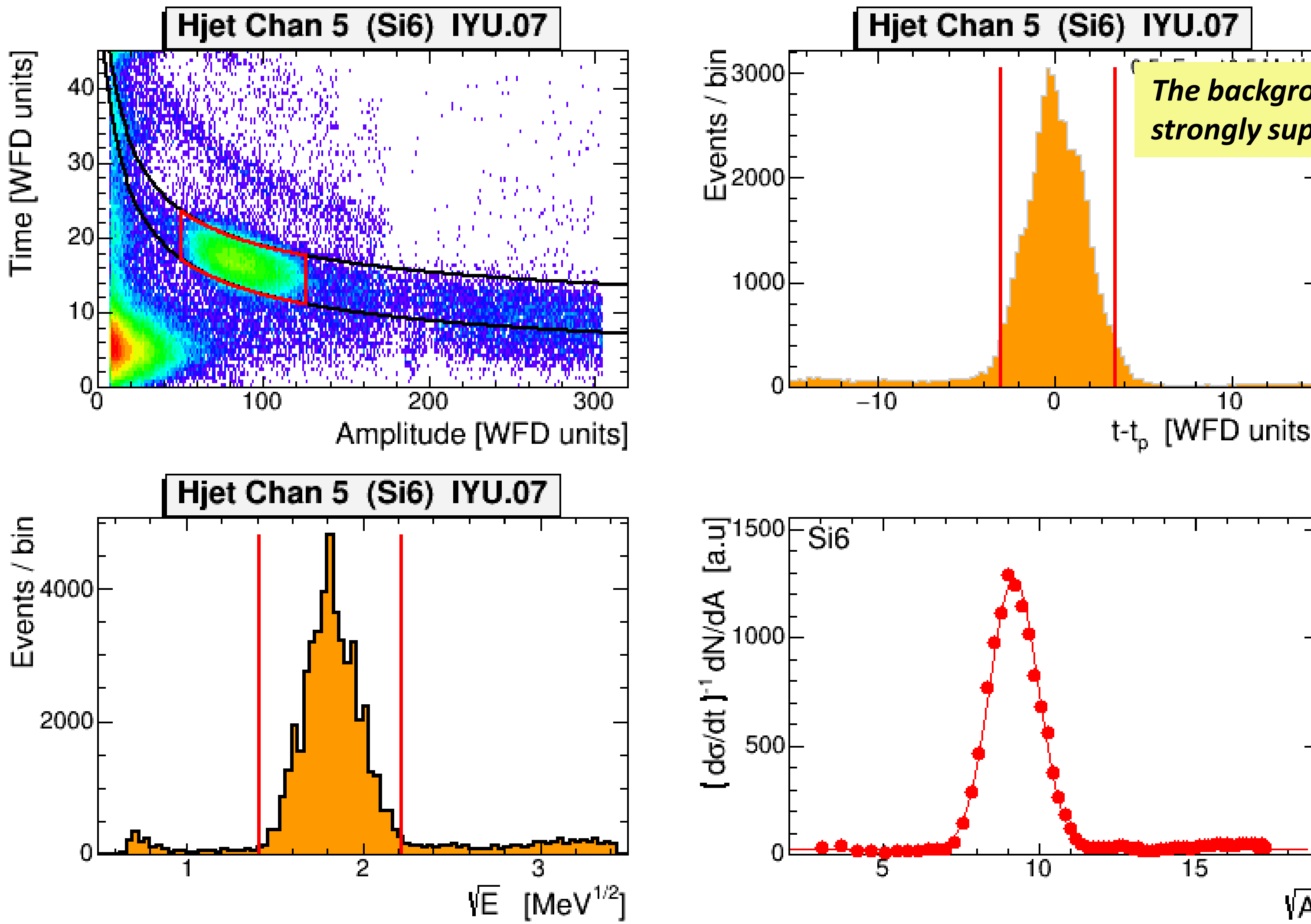




The consistency between simulation and experimental data is not perfect, but sufficiently good for preliminary analysis.

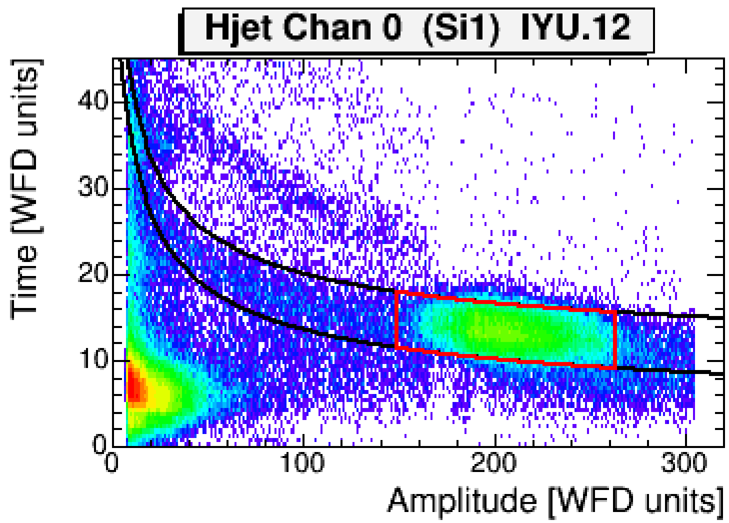
- Event selection cuts are not optimized yet.
- More work is still needed for routine parametrization $n = n(A)$ for all Si strips.

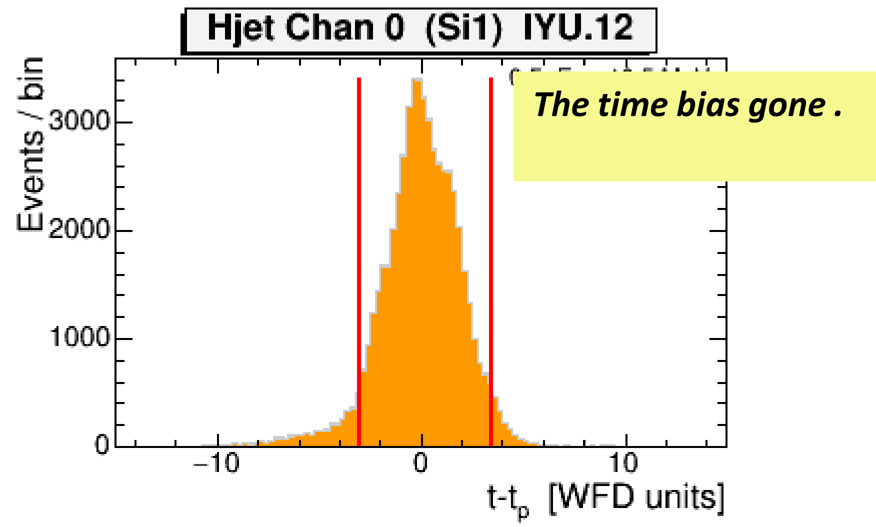
Waveform shape cuts applied. Stopped protons.

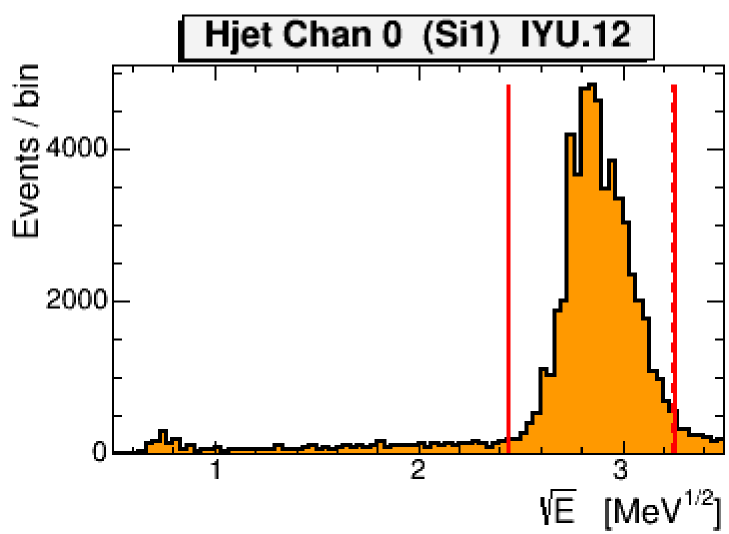


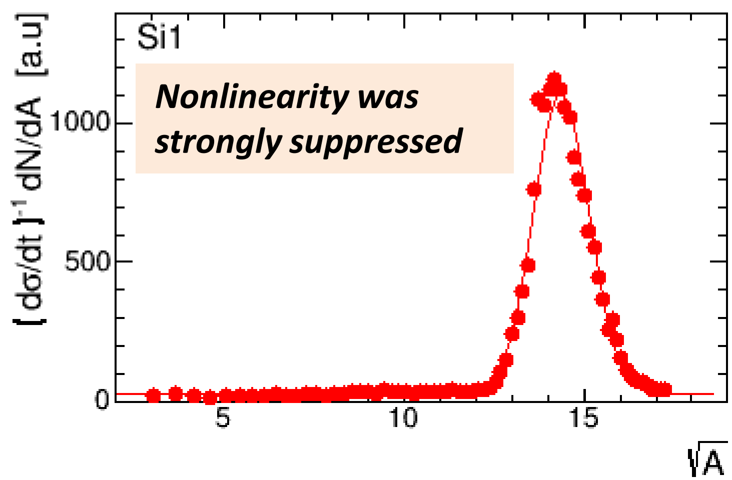
The background was strongly suppressed.

Waveform shape cuts applied. Punched through protons.



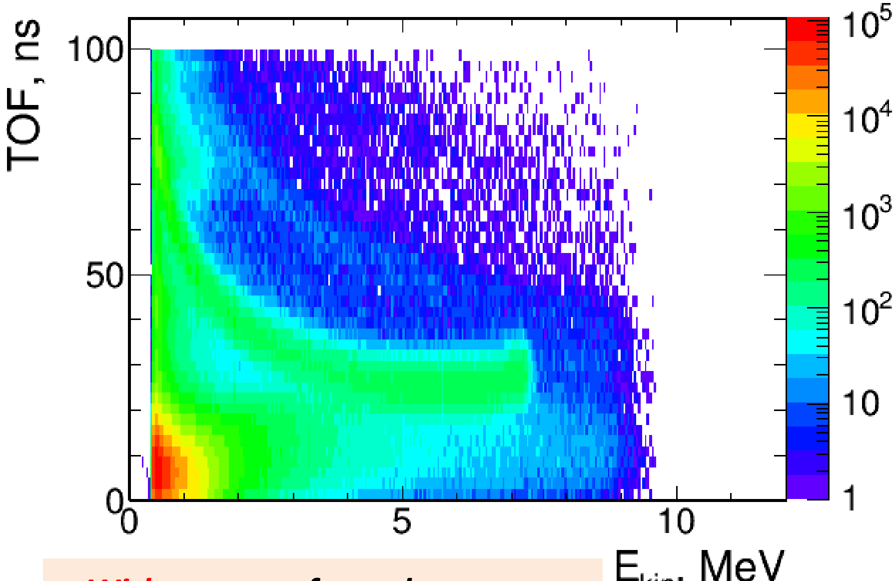




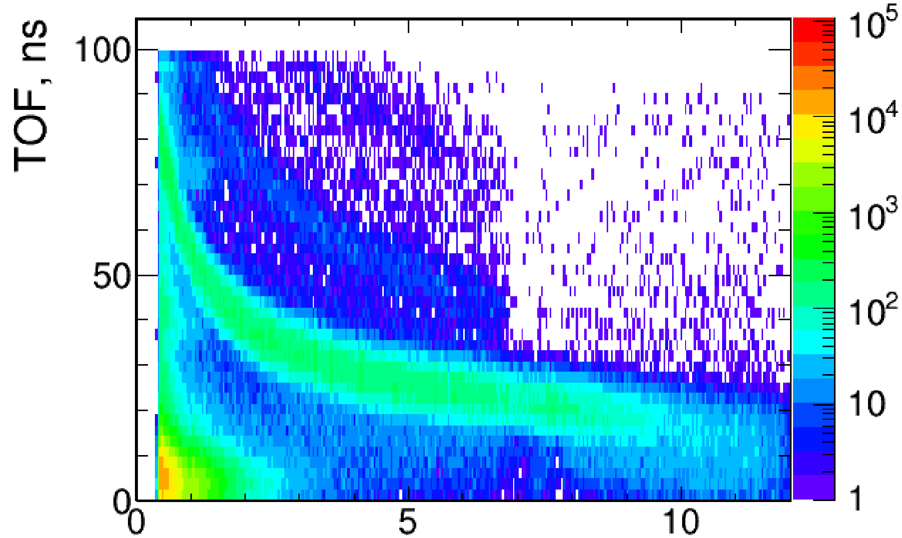


Simulation vs Experimental Data

The sum of all 12 Si Strips in one detector.



***Without** waveform shape cuts.*



***With** waveform shape cuts.*

- The proton energy range can be extended to *0.5 – 10.5 MeV*
  - *0.5 MeV* is defined by internal trigger threshold in FADC
  - *10.5 MeV* is defined by geometrical acceptance of Si detectors
- Background is substantially suppressed for low energy (stopped) protons.
- In the pictures, background is actually counted 12 times, in reality background is smaller.

Systematic Errors in the H-Jet Measurements

$$P_{beam} = P_{jet} \times (a_{beam}/a_{jet})$$

Jet Polarization: there are 2 hydrogen components in the jet:
- atomic with (measured) polarization $P_{BR} \approx 96\%$
- *molecular (unpolarized)*

The molecular hydrogen component of the Jet has much wider width. A flat $\sqrt{A}$ distribution is expected.

The admixture of molecular hydrogen was measured to be $\varepsilon \approx 3\%$ but, but systematic errors of this measurement is not well known. The average polarization $P_{jet} = (1-\varepsilon) \times P_{BR}$ should be used in analysis

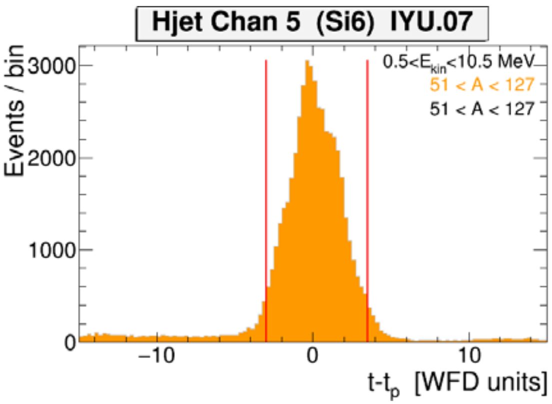
Background: $$\mathbf{A_N^{eff}} = \frac{\mathbf{A_N + rA_N^{bgr}}}{\mathbf{1+r}} = \mathbf{A_N}\frac{\mathbf{1+\alpha r}}{\mathbf{1+r}}; \qquad \alpha = \mathbf{A_N^{bgr}/A_N}$$

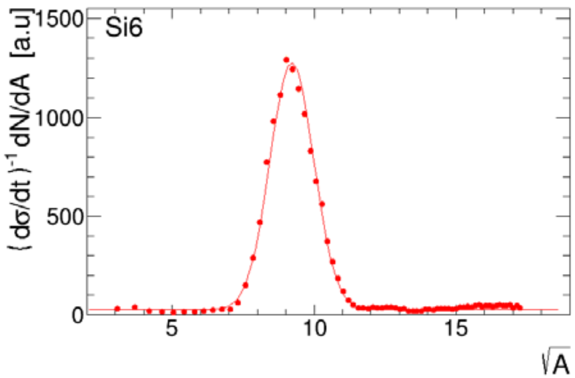
$r \sim 5\%$ is background level
For Jet asymmetry $\alpha = 0$.
For beam asymmetry α is unknown and may be as large as 1
(e.g for beam gas protons and molecular hydrogen).

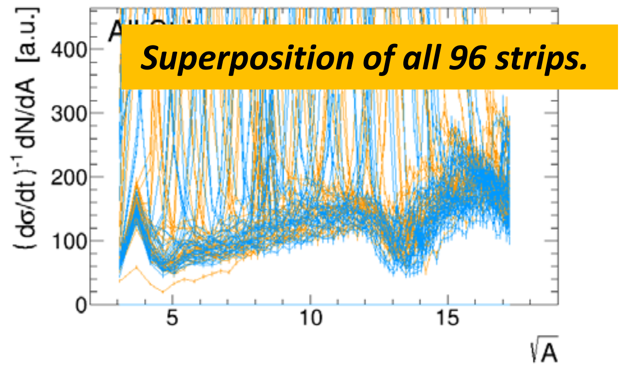
$$\boldsymbol{P_{meas} = P_{beam}(1 + \alpha r)}$$

(some previous experimental estimates gave $\alpha \approx 0$)

An estimate of background contribution to systematic errors
(alternative approach compared to analysis discussed by K.O. Eyser)







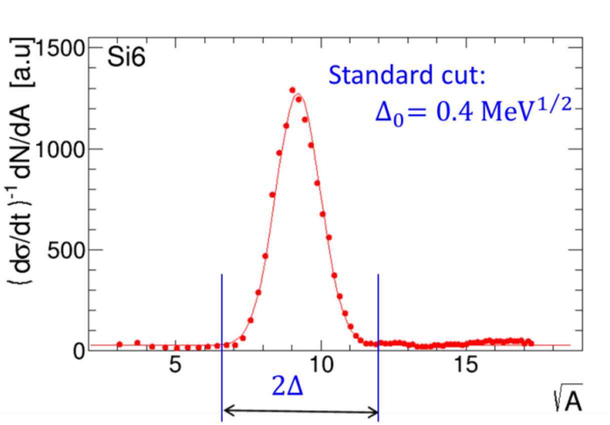
- ***The main signal distributions used to isolate elastic pp events have small and flat background.***
  We can try to subtract it. It should be done separately for all 4 Jet/Beam polarizations.

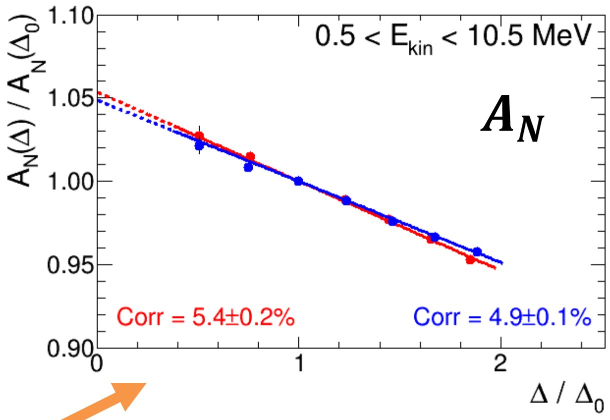
- ***Even more promising is subtraction of average (over detector) background. In this case background may may be properly subtracted .***
  Probably, such a subtraction should be done separately for Blue/Yellow and Left/Right detectors.

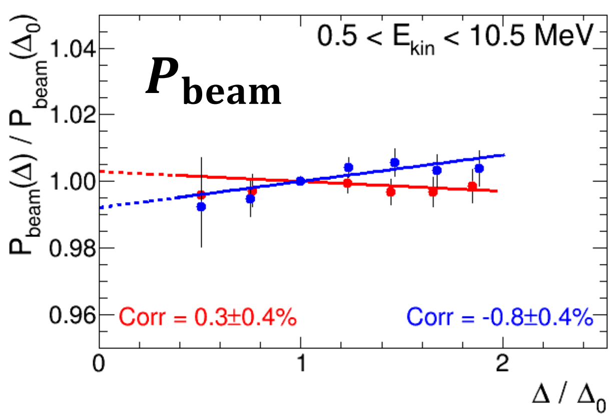
- ***We may expect that molecular hydrogen component will also be subtracted.***

The method, as decribed, was not implemented yet

Fast estimation of background related systematic errors.





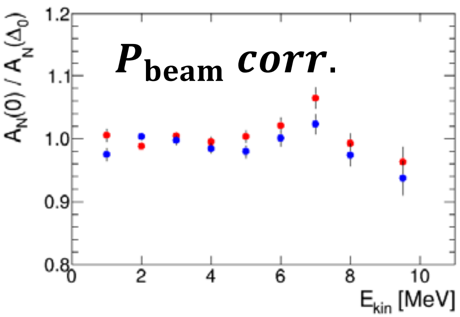


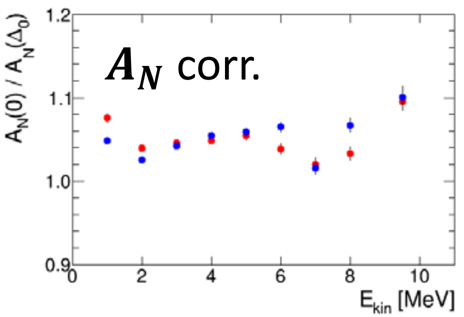
Variation of the cut parameter Δ will result in proportional variation of background contribution but only in a small change of the signal contribution

- *Linear dependences on Δ !*
- *Extrapolation to $\Delta = 0$ will give background (systematic error ?) free result.*
- *The corrections to A_N and P_{beam} are shown on plots. (statistical error only)*

A conservative (??) estimate for background related systematic errors is $\delta P/P \leq 1\%$
Molecular hydrogen background is supposed to be accounted
The $pp \to pp\pi$ background requires special consideration.
A study of "systematic errors in evaluation of systematic errors" has to be done.

Correction dependence on proton energy





Summary

- **New DAQ based on VME 12 bit 250 MHz FADC250 for RHIC Hjet polarimeter was assembled, tested, and employed in RHIC Run 2015**
- **Different calibration methods were tested**
  - ✓ **Energy resolution** $\sim 20\ keV$
  - ✓ **Systematic errors in energy calibration** $\delta E/E < 0.5\%$ **for 1-6 MeV protons**
  - ✓ **Time alignment of electronic channels is better than** $\delta t < 120\ ps$
  - ✓ **z-coordinates of detectors may be monitored with accuracy** $\delta z \sim 100\ \mu m$
  - ✓ **beam angle and x-coordinate may be monitored with accuracy** $0.1\ mrad$ **and** $100\ \mu m$**, respectively.**
- **A method of full reconstruction of punched through protons was developed**
  - ✓ **Recoil proton energy range was increased to 0.5 – 10.5 MeV**
  - ✓ **Background for stopped protons was suppressed**
- **Preliminary study of systematic errors in polarization measurement was performed.**

- ***All presented results were obtained with RHIC Fill 18950-19953 data***
- ***Further adjustment of event selection cuts is still needed.***
- ***Adopting the developed methods for the CAMAC data is forthcoming.***